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Relation of decline characteristics of 2–4.6 MeV protons in SEP events to solar wind parameters

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Abstract

The shape of the particle flux decline in solar energetic particle (SEP) events is of particular importance in understanding the propagation of energetic particles in the interplanetary medium. Power-law time profiles indicate the dominance of diffusive propagation, whereas exponential-law decline emphasizes convection transport and adiabatic deceleration. Values obtained theoretically for the decay time in the latter case are reasonably close to the fitted slopes in nearly half of all events when the solar wind speed stays nearly constant. Dependencies of characteristic decay time τ and spectral index γ on environmental plasma parameters are considered. Parts of exponential-law declines when solar wind speed: (a) decreases with time, (b) is constant, and (c) increases with time through the interval are analyzed separately. Both average values and dispersions of size distributions of τ for these three groups markedly differ in accordance with theoretical expectations.
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1. Introduction

The time profiles of energetic particle fluxes after the maximum of solar energetic particle (SEP) events usually exhibit a several days long decay phase of exponential or power-law shape. The decay in each event is going on in a different way, depending on the state of surrounding interplanetary medium and location of accelerated particle source relative to the observer. Different propagation models result in different shapes of the particle flux declines. For impulsive particle injection on the Sun the solution of the diffusion equation predicts a flux decline described by power law $J(t) \propto t^{-3/2} \exp(-r^2/4\kappa t)$ at times before convection becomes important (r denotes distance, and κ is the diffusion coefficient, cf. Owens,

1979). Except for flares, CME associated shocks may be the origin of accelerated particles as well (sometimes the only ones). During the propagation of charged particles from the Sun, regions of quasi trapping of particles can arise which may either be connected with the shock front or appear between the shock front and strong magnetic fields at the Sun (Reames et al., 1996; Kahler, 1996). The decay of the intensity of trapped particles also obeys to power law (Reames et al., 1996; Daibog et al., 2003). Statistical studies, however, indicate, that the decay profiles of proton fluxes are predominantly exponential. On a sample of ∼700 events of 1–5 MeV proton fluxes only about 10% of the declines were power-law, 90% were exponential, while a small fraction of exponentials had power-law tails above ∼20 MeV (Daibog et al., 2003).

Charged particles propagating in the solar wind plasma, permanently present in heliosphere, are convected

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and adiabatically decelerated in the diverging magnetic field. Due to convection, in the exponential term of the profile, instead of $-r^2$ one obtains $-(r - Vt)^2$, where V is solar wind speed. Under the most general conditions, from the convective motion of accelerated particles it follows that the τ time constant characterising decay should decrease with increasing V, and on the other hand, adiabatic deceleration should cause τ to decrease due to energy spectra falling with energy. τ should also decrease with the increase of spectral index γ. In case convection and adiabatic deceleration terms dominate over gradients, scattering, and drift in the transport equation, an exponential decay of flux is obtained: $J \propto \exp(-t/\tau)$, with a decay time of

$$\tau = 3r/2V(2 + \alpha\gamma), \tag{1}$$

where $\alpha = T + 2mc^2/(T + mc^2) \approx 2$ at nonrelativistic energies (Forman, 1970; Jokipii, 1972). This can be interpreted as adiabatic deceleration enhances the effect of convection resulting in an effective convection velocity $V^* = 2(2 + \alpha\gamma)V$ (Owens, 1979 for impulsive injection). Lee (2001) considers transport equation taking into account adiabatic deceleration only and obtains the same dependence (assuming $\alpha = 2$). All results discussed below refer to 1 AU, that is, we cannot check the variation of τ with r. The comparison of proton fluxes at Ulysses in the profiles of SEP events between about 1.3 and 3 AU near solar maximum with those at 1 AU (IMP-8) by McKibben et al. (2003) suggests that τ depends very little on r above 30 MeV. However, especially below ~5 MeV, the IMP profiles look steeper, which could be attributed to a latitude effect, but an increase of τ with r cannot be excluded.

Strictly speaking, the above formula is correct only at very late phase of decay, however, if convection and adiabatic deceleration really take place, one can expect some correlation between τ and values of V and γ, respectively, after particle peak intensity. We consider such correlations and compare them with the formula soberly understanding the limits of its application.

2. Observations

The analysis of flux variations was made on a homogeneous data set of 2–25 MeV protons obtained by the CPME instrument aboard IMP 8 between 1974 and 2001. Time intervals during the decay phase of SEP events following flares, CMEs and interplanetary shocks were examined. From the whole database of more than 600 exponential declines (see Daibog et al., 2003) only those were selected which were well approximated with an exponential during a period of at least 24 h. As indicated in earlier analyses, we tried to minimize the influence of shocks by only using time intervals where the particles directly related to shock (energetic storm parti-

cles) could be neglected. Events significantly "contaminated" by shock-accelerated particles were omitted in this analysis. The second requirement was regular solar wind behaviour: the variation of the solar wind speed V (as observed during the exponential periods) should fulfil one of the following criteria: (A) V monotonously decreases ($dV/dt < 0$), (B) V is constant ($dV/dt = 0$) within 5%, or (C) V monotonously increases ($dV/dt > 0$). Sometimes A, B, and C time intervals contained full periods of exponential declines and vice versa (the latter ones contained the formers), sometimes they overlapped partly. As a rule, we took into account those periods that overlapped for longer than 12 h. According to these criteria the numbers of declines in the groups were: 77
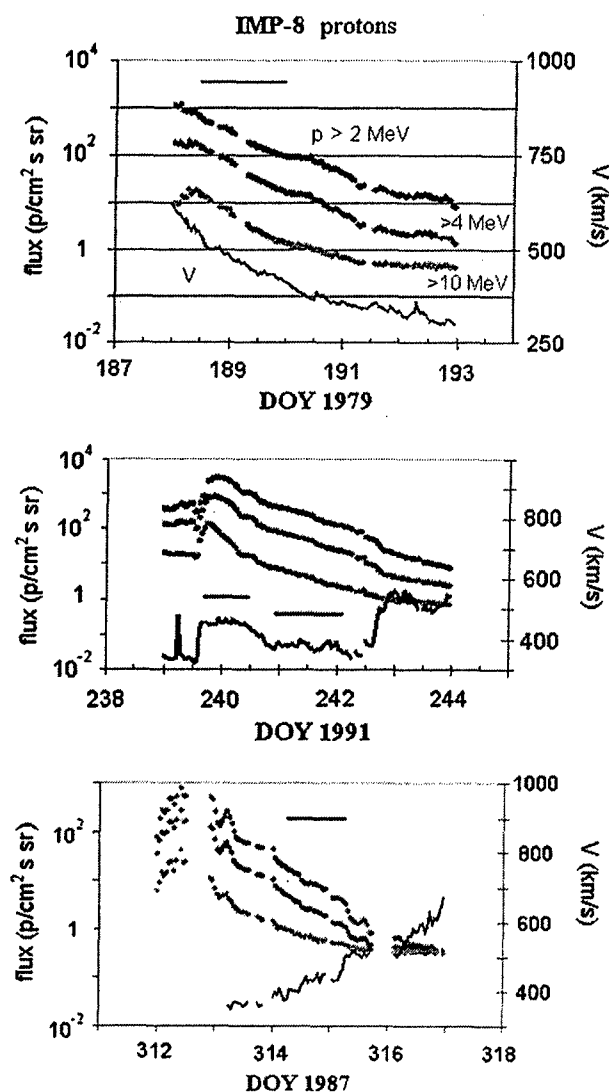

Fig. 1. Time profiles of protons in three integral energy channels of CPME for $dV/dt < 0$ (top), $V =$ const. (center), and $dV/dt > 0$ (bottom). Horizontal bars: periods fitted with exponentials. Lower curves: solar wind speed.

(A), 49 (B) and 20 (C), respectively. The three panels of Fig. 1 demonstrate patterns of these three groups of solar wind behaviour during exponential decays. The flux profiles were then fitted with exponentials and the τ values determined from least-squares fits. Here, we only used the 2–4.6 MeV proton channel.

3. Results and discussion

The solar wind speed values spread over wide intervals. Average values of V are 490, 417 and 498 km/s, for the three groups, respectively. Parts of exponential-law declines with different behavior of V throughout the declines were analyzed separately. Size distributions of values of τ for all three groups are given in Fig. 2. While the values of $\langle V \rangle$ for groups A and C are practically the same, the average value of τ for the C group ($\langle \tau \rangle \approx 16.5$ h) markedly differ from both A and B ($\langle \tau \rangle \approx 19.1$ and 19.6 h, correspondingly).

In spite of that all available statistics for nearly three full solar cycles have been used, the analysis of (V) and $\tau(\gamma)$ dependencies has limitations. The three panels of Fig. 3 exhibit scatter plots of $\tau(V)$ for all values of γ in all groups, whereas Fig. 4 gives the same for $\tau(\gamma)$ for all values of V. All scatter plots are relatively broad which may be explained by a large dispersion of γ for $\tau(V)$ as well as by a large dispersion of V for $\tau(\gamma)$ plot. Furthermore, the different position (eastward or westward) of the observer relative to the flare site (McCracken et al., 1971) also widens the distributions. Another possible cause of the large scatter in Figs. 3 and 4 is the superposition of particles accelerated by interplanetary shocks (especially for low amplitude events in groups A and C). The intensities of low-energy (>2 MeV) protons are enhanced, with a phase (often lasting up to three days) of ramping up before the shock However, some restricting dependence can be noted in a sense that the highest values of τ do correlate with small values of V whereas the highest values of V correlate
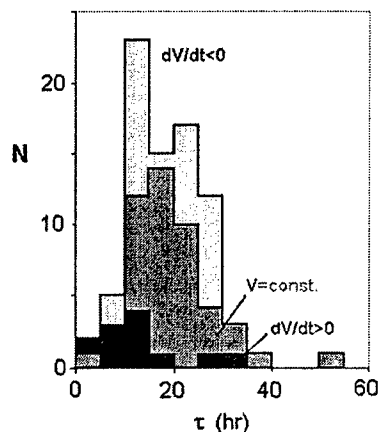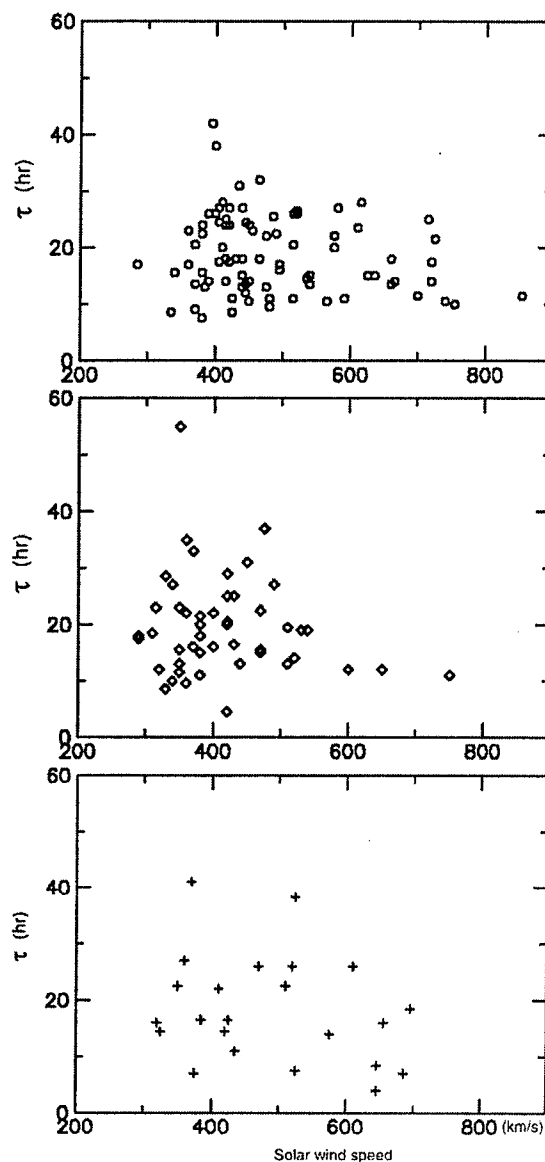

Fig. 3. Dependence of τ on V for decays with $dV/dt < 0$ (top), $V = $ const. (center), and $dV/dt > 0$ (bottom).

with small values of τ. The same holds for the $\tau(\gamma)$ dependence. Definitely, a tendency of a reverse τ dependence on both V and γ can be observed.

The complex dependence of τ on V and γ has been explored by calculating correlations between experimental values of τ (τ_{exp}) and those calculated according to the formula $\tau_{th} = 3r/2V\ (2 + \alpha\gamma)$. The two panels of Fig. 5 display the size distributions for the three groups. Average values the τ_{exp}/τ_{th} ratios are equal to 1.17, 1.04, and 0.92, correspondingly, thus the sign of dV/dt plays some role in determining τ. In group A $\langle \tau_{exp}/\tau_{th} \rangle > 1$ practically means as if a higher effective value of V should be considered.

The two panels of Fig. 5 suggest that about half of the total number of declines match the value obtained
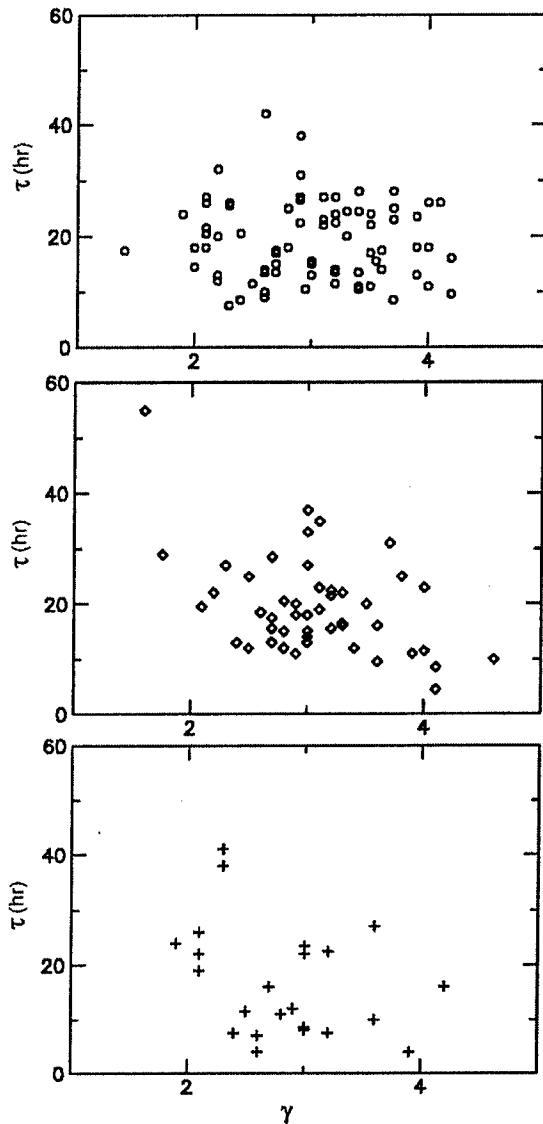

Fig. 2. Distributions of τ values for the three groups.

Fig. 4. Dependence of τ on γ for decays with $dV/dt < 0$ (top), $V = $ const. (center), and $dV/dt > 0$ (bottom).

Fig. 5. Histogram of the distribution of τ/τ_{th} values for $V = $ const. (left panel), $dV/dt < 0$ (upper line, right panel) and $dV/dt > 0$ (lower line).

using the formula (1) within an accuracy of about 25%. The dispersions of these size distributions are 0.47, 0.42 and 0.50, respectively. Group C displays the largest departure from formula (1). In spite of that $\langle V \rangle$ has similar values in A and C, and $\langle \gamma \rangle$ is nearly the same in all groups (3.0, 3.1, and 2.8, respectively), the shape of the distribution of C is quite different from that of A. A possible explanation for such a difference is that the connection point of the observer scans to the east and the observed increase of the solar wind speed means that the faster solar wind presses the slower one westward together with the frozen magnetic field lines (in extreme cases corotating shocks may be formed at near 1 AU). In such a case a very dynamical picture develops in a region of increas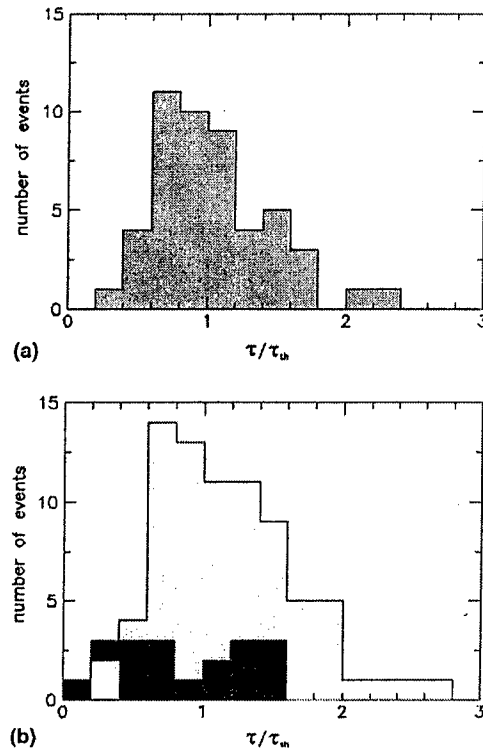ing V and probably conditions in this region are not quasi-stationary. Here, both regular convection and adiabatic deceleration regimes are violated, whereas in groups A and C the conditions can be considered stable. The small number of exponential declines in group C and the considerably smaller value of $\langle \tau \rangle$ can also be a consequence of unstable conditions in interplanetary space in the case of increasing solar wind speed. However, in spite of such unstable conditions sometimes we observe time profiles, which have smooth exponential character (see Fig. 1(a)).

4. Conclusions

The analysis of the decay phases of nearly 150 SEP events confirmed the theoretical expectation that this phase is predominantly determined by convection and adiabatic deceleration in the solar wind plasma.

About the half of the total number of exponential declines analysed satisfy theoretical conditions and the decay time falls within 25% of the theoretical values. The following tendencies in the influence of solar wind speed, V, on the rate of decline of SEP events were revealed:

- The average values of characteristic decay times $\langle \tau \rangle$, for groups of events with decreasing, constant and increasing solar wind speed V are 19.1, 19.6 and 16.5 h, respectively.

- τ decreases with the increase of solar wind speed and of the spectral index γ in agreement with theoretical considerations.

The analysis performed indicated that neither in individual events nor in the entirety of exponential declines solar wind speed is solely responsible in determining the value of characteristic decay time.

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14. ABSTRACT

   The shape of the particle flux decline in solar energetic particle (SEP) events is of particular importance in understanding the propagation of energetic particles in the interplanetary medium. Power-law time profiles indicate the dominance of diffusive propagation, whereas exponential-law decline emphasizes convection transport and adiabatic deceleration. Values obtained theoretically for the decay time in the latter case are reasonably close to the fitted slopes in nearly half of all events when the solar wind speed stays nearly constant. Dependencies of characteristic decay time τ and spectral index γ on environmental plasma parameters are considered. Parts of exponential-law declines when solar wind speed: (a) decreases with time, (b) is constant, and (c) increases with time through the interval are analyzed separately. Both average values and dispersions of size distributions of τ for these three groups markedly differ in accordance with theoretical expectations.
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